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Reports

Accuracy of Topographic Measurements in a Model Eye with the Laser Tomographic Scanner

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The authors evaluated the accuracy of topographic measurements with the laser tomographic scanner using a model eye. Diameter, depth, and shape at different axial lengths of four sample holes that simulated optic nerve heads in phakic and aphakic conditions were determined by confocal imaging. The computer-generated cross-section profiles of the simulated optic nerve heads corresponded well with the actual contours as photographed by scanning electron microscopy. The average relative error in diameter was 2.0% (range: 0.3–2.9%) for the phakic model eye and 3.6% (range: 0.6–8.2%) for the aphakic model eye. The average relative error in depth was 11.7% (range: 1.2–20.1%) for the phakic model eye and 10.1% (range: 1.7–22.6%) for the aphakic model. Invest Ophthalmol Vis Sci 32:2992–2996, 1991

Several instruments have been introduced for computerized image analysis of the optic nerve head. One of these, the laser tomographic scanner, employs an optical principle known as confocal imaging to obtain highly reproducible topographic measurements of the fundus.[1] However, high reproducibility does not ensure that the descriptive measurements accurately represent the structure being measured. In the current study, we evaluated the accuracy of topographic measurements with the laser tomographic scanner using a model eye.

Materials and Methods. To study the accuracy of topographic measurements, we used a plastic model of the human eye; the model was described previously by Shields et al.[2] The model was 24 mm wide and 24 mm deep and had been constructed from sheets of red-orange plastic material (Fig. 1). The optics of the model consisted of a plastic cornea, fashioned from polymethylmethacrylate, and an intraocular lens that could be removed to simulate an aphakic eye. The keratometric readings of the plastic cornea were 45.60/45.60, and the power of the intraocular lens was +19.5 diopters (D). The retina was simulated by a flat plate of red-orange plastic into which four holes of known size and shape had been drilled. Two of the holes had round contours, one had a shallow cone-shaped contour, and one was of rectangular contour. The holes were located 3 mm off the optical axis of the model eye. The axial length could be varied by inserting the plate into one of three sets of slots in the model eye. The model was filled with saline, and A-scan measurements were used to determine the three axial lengths. The three positions of the retinal plate resulted in axial lengths of 22.29, 24.49, and 26.45 mm. The corresponding refractive errors were +0.50, −5.50, and −10.25 D in the phakic model and +12.00, +8.00 and +4.75 D in the aphakic model.

A laser tomographic scanner (Heidelberg Instruments GmbH, Heidelberg, Germany) was used to acquire and evaluate topographic images of the simulated optic nerve heads. This instrument has been described previously.[3–5] In brief, the laser tomographic scanner uses a low-intensity helium-neon laser beam that is focused on and scanned across the retina in three dimensions. The light reflected from each point of the scan is detected, digitized, and displayed on a video monitor as one pixel of an image. The detection system is based on the optical principle of confocal detection; this assures that only light reflected from objects within a sharply defined focal plane is detected. Thus, the image being displayed represents an optical section image parallel to the retinal surface. By moving the focus of the instrument posteriorly, section images of various focal planes can be acquired. Each image consists of 256 × 256 pixels and covers a field of view of between 10 and 20 degrees. To obtain a topographic image of the optic nerve head area, 32 consecutive section images are acquired. The acquisition time for these 32 section images is about 4 sec. From the stack of 32 section images, the height at each of the 65,536 pixel positions is calculated and displayed on the monitor as a topographical map. A cursor can be moved by the operator across the map. At each position, the lateral coordinates of the cursor, as well as the height value at this position, are displayed on the monitor in units of micrometers (μm). The resolution of these measurements is limited to the size of one pixel, which is approximately 11 μm (uncorrected value). Hence, distances such as horizontal and vertical width of the optic nerve head can be

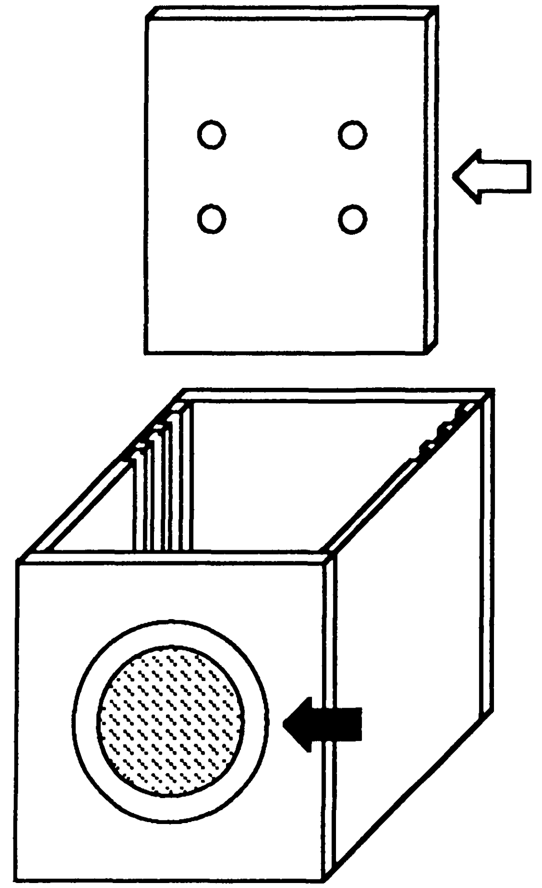

Fig. 1. Schematic of the model eye with plastic retina and four sample holes (open arrow), and plastic cornea (closed arrow).

measured interactively. Also, instant two-dimensional contour lines (cross-sections) in x- and y- direction can be displayed for each cursor position.

The model eye was placed in front of the laser tomographic scanner with a magnetic mount. For each sample hole, the eye was adjusted until the hole being examined appeared in the center of the scanning image and the laser beam was centered with respect to the plastic cornea. The field of view was chosen to be 10 degrees for all measurements. The operator selected the longitudinal scan range by determining the focus position of the first and the last of the 32 section images. Typically, this range was 1.5 mm. The optics of the laser tomographic scanner could compensate only for refractive errors from −10.00 to +10.00 D. Therefore, the phakic model with an axial length of 26.45 mm (−10.25 D), as well as the aphakic model with an axial length of 22.49 mm (+12.00 D), could not be scanned and were excluded from the study. Each of the four sample holes were scanned in the phakic and the aphakic model at the two remaining axial length positions, which resulted in 16 different measurements. Additionally, five independent scans were obtained of sample hole 1 at each of the possible axial lengths in the phakic and the aphakic model eye to estimate the reproducibility of the measurements.

After acquiring the image series for each hole at each retinal position, the image series were processed and the resultant image for each measurement stored on an optical disk drive. Thereafter, each topographic image was recalled and displayed on the video monitor for further evaluation. The cursor was moved to the outer borders of the sample hole along the horizontal and the vertical meridians; the lateral coordinates and the height values of these edge locations were noted. The distances between the two opposite locations were calculated and represented the horizontal and vertical diameters of the sample hole. From the horizontal and vertical diameters, the coordinates of the center of the sample holes were calculated. The depth of the sample hole was taken as the difference between the height value of the central pixel and the averaged height of two opposite locations at the edge of the hole.

The lateral measurements with the laser tomographic scanner were based on the assumption that the eye being measured was of average dimensions, based on the Gullstrand model. To correct for magnification error in the model eye, we used Littmann's method.[6] In brief, the axial lengths and refractive errors were used to determine artificial corneal radii, which in turn were used, in combination with the refractive errors, to determine the true magnification. Correction factors of .941, 1.045, 1.003, and 1.100 were applied to the diameter values for the model eye of corresponding refractive error of +0.5, −5.5, +8.0, and +4.75 D. Another correction was applied to the values for the horizontal diameters to eliminate a systematic error related to the model retina being a flat plate instead of a curved object. The 3-mm offset of the sample holes with respect to the optical axis of the model eye caused the scanning laser beam to intersect the retinal plane at an oblique angle. This resulted in the horizontal diameter appearing smaller than the vertical diameter. The incident angle was calculated using the known offset of the sample holes and the axial length of the model eye. The secant of this angle was applied to the horizontal diameter as an additional correction factor. For each sample hole, the corrected horizontal and vertical diameters were averaged to obtain the corrected diameter.

With the laser tomographic scanner, the magnification error in depth is dependent on the focal length of the eye being examined. The laser tomographic scanner assumes a focal length of 22.3 mm (16.7 mm in air and a refractive index of the aqueous and vitreous of 1.336). In the model eye, we measured the focal lengths of the phakic and the aphakic model to be 23.5 mm and 32.0 mm, respectively. The corresponding correction factors to be applied are proportional to the square of the ratio of the actual focal length and the focal length of the standard eye. A correction factor of 1.069 for the depth measurements in the phakic eye and a factor of 2.049 for correcting the depth measurements in the aphakic eye were calculated and applied.

The vertical cross-section profile was displayed for the central pixel of the sample hole. The contour at this position was traced on a sheet of transparent plastic. This procedure was repeated for each topographic image.

To estimate the accuracy of contour measurements, each sample hole was cut down the middle and photographed on edge by scanning electron microscopy. The photograph of sample hole 1 was enlarged to match the size and shape of the corresponding cross-section profile previously traced from the monitor of the laser tomographic scanner. The same enlargement factor was used for the photographs of the remaining sample holes. The cross-section profiles were superimposed on the scanning electron microscopy photographs to provide a subjective view of the accuracy with which the laser tomographic scanner reproduced the cross-sectional contour of the sample hole. The dimensions of the sample holes were measured with a Zeiss measuring light microscope and a precision x-y-stage. Repeated measurements (n = 5) with this measuring light microscope resulted in a standard deviation of ±2.3 μm.

Results. The contours and actual dimensions of the four sample holes obtained with the measuring microscope are shown in Table 1. Table 2 shows the corrected dimensions of the four sample holes in the phakic model eye; Table 3 shows the corresponding data for the aphakic model. The corrected dimensions of each sample hole were compared to the actual sample hole dimensions to obtain the relative error of the single measurements. The relative errors in diameter were between 0.3% and 2.9% (mean: 2.0%) for the phakic model eye (Table 2) and between 0.6% and 8.2% (mean: 3.6%) for the aphakic model eye (Table 3). The relative errors in depth were between 1.2% and 20.1% (mean: 11.7%) for the phakic model eye and between 1.7% and 22.6% (mean: 10.1%) for the aphakic model.

Table 1. Actual dimensions of the sample holes

Sample	*Contour*	*Diameter (μm)*	*Maximum depth (μm)*
1	Hemispherical	2015	983
2	Hemispherical	2007	953
3	Conical	2004	1069
4	Rectangular	2265	1029

Table 2. Corrected dimensions (μm) of sample holes in the phakic model eye measured with the laser tomographic scanner

Axial length (mm)	*Sample*	*Diameter**	*Error (%)†*	*Depth*	*Error (%)†*
22.3	1	1992	1.1	928	5.6
22.3	2	2013	0.3	1048	10.0
22.3	3	2053	2.4	949	11.2
22.3	4	2199	2.9	878	14.7
24.5	1	1952	2.6	995	1.2
24.5	2	2043	1.8	819	14.1
24.5	3	2055	2.5	854	20.1
24.5	4	2204	2.7	859	16.5

* Corrected diameter was obtained by averaging corrected horizontal and vertical diameter of each sample hole.

† Error is obtained by comparing corrected dimensions to actual dimensions.

To account for the propagation of errors and to estimate the reproducibility of the relative error, the repeated measurements of sample hole 1 were used to assess the coefficient of variation of the relative error. Table 4 shows the results of the repeated measurements. The relative errors of the mean of the repeated measurements were 1.1% and 3.1% for the phakic model eye and 3.5% and 5.1% for the aphakic model. The average relative errors (2.1% for phakic, 4.3% for aphakic model) are only slightly higher than the average errors of the single measurements shown in Tables 2 and 3.

Figures 2A and 2B show two sample holes photographed with scanning electron microscopy after bisecting them. Superimposed are two cross-section profiles traced from the monitor of the laser tomographic scanner. The solid line represents the cross-section obtained in the phakic model eye with an axial length of 22.3 mm; the interrupted line shows the cross-section obtained in the phakic model eye with an axial length of 24.5 mm. Figure 2A depicts sample

Table 3. Corrected dimensions (μm) of sample holes in the aphakic model eye measured with the laser tomographic scanner

Axial length (mm)	*Sample*	*Diameter**	*Error (%)†*	*Depth*	*Error (%)†*
24.5	1	2086	3.5	1013	3.1
24.5	2	2019	0.6	1053	10.5
24.5	3	2026	1.1	1180	10.4
24.5	4	2137	5.7	797	22.6
26.5	1	1913	5.1	840	14.5
26.5	2	1993	0.7	969	1.7
26.5	3	1927	3.8	1174	9.8
26.5	4	2080	8.2	1112	8.1

* Corrected diameter was obtained by averaging corrected horizontal and vertical diameter of each sample hole.

† Error is obtained by comparing corrected dimensions to actual dimensions.

Table 4. Results of repeated measurements (n = 5) of sample hole 1 (the actual diameter of this sample hole as determined with the measuring light microscope was 2015 ± 2 μm)

Axial length	*Phakic/ aphakic*	*Diameter* (mean ± SD)*	*Absolute error of mean†*	*Relative error of mean†*	*Coefficient of variation of relative error*
22.3 mm	Phakic	1992 ± 31 μm	23 μm	1.1%	135.0%
24.5 mm	Phakic	1952 ± 56 μm	63 μm	3.1%	89.1%
24.5 mm	Aphakic	2086 ± 37 μm	71 μm	3.5%	52.1%
26.5 mm	Aphakic	1913 ± 43 μm	102 μm	5.1%	42.1%

* Diameter after magnification correction.
† Compared to actual diameter.

hole 1, which had a hemispherical contour. Both cross-section profiles approximate closely the actual contour of the sample. However, at the hole's bottom, as well as at the edges, minor discrepancies can be seen. In Figure 2B, sample hole 4 with a rectangular contour is displayed. The vertical slope of the contour is less accurately depicted by the cross-section profiles than the cross-section profile along the bottom of the hole, which corresponds to the actual topography of the sample.

Discussion. The superimposed, computer-generated, cross-section profiles were similar in shape to the corresponding cross-sections of the scanning micrographs, suggesting that the shape and size of these

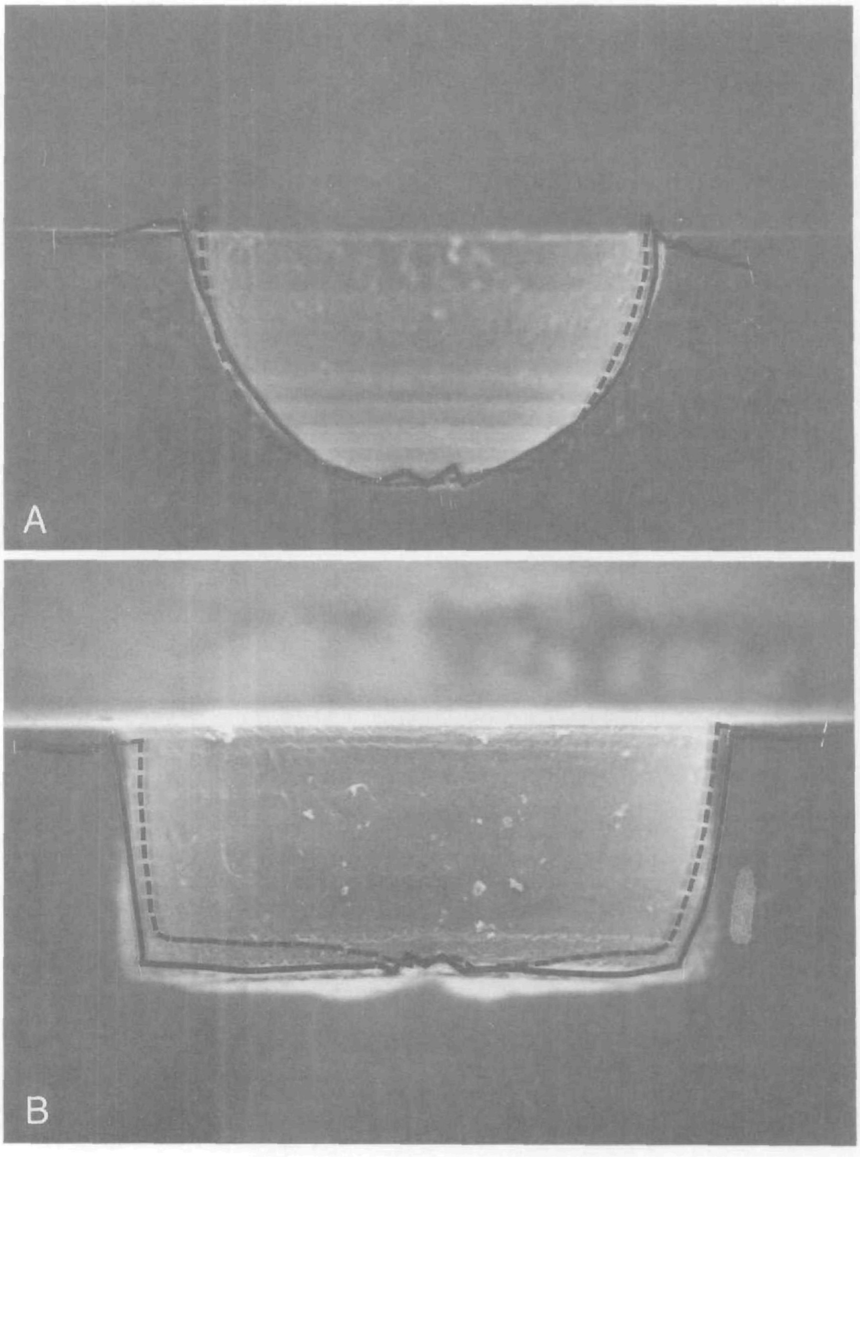

Fig. 2. Scanning electron micrograph of sample holes 1 (**A**) and 4 (**B**). Superimposed are two cross-section profiles traced from the monitor of the laser tomographic scanner. The solid line represents the cross-section obtained in the phakic model eye with an axial length of 22.3 mm, the interrupted line shows the cross-section obtained in the phakic model eye with an axial length of 24.5 mm.

images represented the actual topography of the simulated optic nerve heads (sample holes) with reasonable accuracy. Near the edge of the hole, the profile had a tendency to rise above the surface of the model, creating an apparent elevation adjacent to the sample hole that was not present. Such an elevation also was noted by Shields et al,[2] who studied this model with the Optic Nerve Head Analyzer (G. Rodenstock Instrumente GmbH, Munich), an imaging device that uses another method for quantitating topography.[2] In our study, we speculate that this artifact occurs at locations where there is prominent specular reflection of incident light—for example, at the edge and the bottom of the sample holes.

As noted by Shields et al,[2] accuracy is more difficult to estimate than reproducibility because it requires a means of correlating size and shape measurements with the images. Because this is not possible in living human eyes, and because human postmortem eyes or animal eyes are limited by fixation artifacts, there is value in using a plastic eye model to access accuracy. However, a plastic model cannot perfectly simulate the human eye. Because of the many limitations and simplifications of a model eye, the results obtained with such a model might not be directly comparable to those obtained with a human eye. For example, in the model eye we had a spherical cornea, whereas the human cornea is aspheric. The spherical cornea in the model has no astigmatism and fewer other aberrations, resulting in better resolution. In contrast, the flat retina of the model introduces errors in field curvature, which have not been taken into account in the laser tomographic scanner, with consequent distortion. Hence, the accuracy values obtained in this study can be only an estimate of the accuracy of the instrument.

Measuring accuracy in a model eye can be misleading in another respect. Quantitative measurements in the living eye are highly dependent upon correction for magnification error. Correction for lateral magnification error can be accomplished by knowing the axial length, refractive error, and corneal curvature.[6] However, to correct depth measurements obtained with confocal sectioning, the actual focal length of the eye under examination must be known. In the present study, the data of all optical elements of the model eye were accessible. In a human eye, this information is not available and has to be substituted with average data.[7] Therefore, the accuracy of measurements in individual eyes strongly depends on how good the average values describe the eye under investigation. Especially in aphakia, this can lead to large errors in depth measurement.

The results in our study suggest that the laser tomographic scanner reproduces with reasonable accuracy the three-dimensional size and shape of the optic nerve head models.

Key words: laser tomographic scanner, optic nerve head, topography, accuracy, cross-section profile

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References

1. Weinreb RN and Dreher AW: Reproducibility and accuracy of topographic measurements of the optic nerve head with the laser tomographic scanner. *In* Scanning Laser Ophthalmoscopy and Tomography, Nasemann J, Burk ROW, editors. Munich, Quintessenz-Verlag, 1990, pp. 177–182.
2. Shields MB, Tiedeman JS, Miller KN, Hickingbotham D, and Ollie AR: Accuracy of topographic measurements with the optic nerve head analyzer. Am J Ophthalmol 107:273, 1989.
3. Weinreb RN, Dreher AW, and Bille J: Quantitative assessment of the optic nerve head with the laser tomographic scanner. Int J Ophthalmol 13:125, 1989.
4. Dreher AW, Bille JF, and Weinreb RN: Active-optical depth resolution improvement of the laser tomographic scanner. Applied Optics 28:804, 1989.
5. Zinser G, Wijnaendts-van-Resandt RW, Dreher AW, Weinreb RN, Harbarth U, Schroeder H, and Burk ROW: Confocal laser tomographic scanning of the eye. Proc SPIE 1161:337, 1989.
6. Littmann H: Zur Bestimmung der wahren Groesse eines Objektes auf dem Hintergrund eines lebenden Auges. Klin Monatsbl Augenheilkd 180:286, 1982.
7. Zinser G, Harbarth U, and Schroeder H: Formation of three-dimensional data with the laser tomographic scanner (LTS). *In* Scanning Laser Ophthalmoscopy and Tomography, Nasemann J, Burk ROW, editors. Munich, Quintessenz-Verlag, 1990, pp. 183–191.